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RPPR Final Report
as of 04-Feb-2019

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Major Goals: In this project we propose to investigate recent developments and improvements in the simulation techniques for gas turbine engines by developing new simulation methods and software for the application at hand, while simultaneously leveraging recent developments in the areas of geometry modeling, coupled mechanical simulation (i.e., fluid—structure interaction (FSI)), and integration of geometry modeling and simulation using the concept of Isogeometric Analysis (IGA). We propose to develop, implement, and validate the computational framework, which consists of the following items and features: a. Multiscale modeling of compressible turbulent flows in geometrically complex configurations; b. Hierarchical modeling of geometrically complex gas turbine blade structures based on IGA; c. Accurate and efficient treatment of fluid—structure interfaces present in the modeling and simulation of the coupled FSI phenomena; d. Algorithmic implementation suitable for HPC.

Accomplishments: This current project has led to the development of novel numerical methodologies, algorithms, and tools for geometric modeling, and compressible-flow and FSI analysis. It opened the doors for analyzing gas turbines with more fidelity and precision, which can lead to better understanding of the detailed physics of compressible flows in these complex engineering systems. Besides being able to model more physically realistic behavior, the computational methodologies and simulation tools developed naturally lend themselves to design optimization of these engineering systems. The methods developed were successfully deployed on an actual, full-scale gas turbine design provided by ARL.

The fundamental research developments in this project have yielded the following outcomes:

Outcome 1: Pertains to the project thrust area dealing with the development of methods and algorithms for solving compressible-flow and FSI problems on moving domains. We developed a new formulation for compressible flow and FSI, which can robustly handle a wide range of Mach numbers - from nearly incompressible flow to high-Mach-number compressible flows. A novel way of handling near-wall models and sliding interfaces for mechanical components in relative motion were introduced for the first time in this project. Extensive experimental validation of the developed computational technology was performed. The methods and software are now being used directly to simulate actual, novel gas-turbine designs proposed by ARL in the context of the Articulating Blade Concept.

Outcome 2: Shows a direct application of the above thrust areas (geometry modeling and compressible flow and FSI methods development) to a specific gas-turbine design simulated at the operating flow and rotor speeds, and thermal conditions. Using the parametric geometry modeling tool it was a simple matter to apply a pitch angle of 10 degrees to a baseline ARL design. Articulating the pitch angle resulted in 5.6% improvement of the turbine efficiency compared to the baseline design.

Outcome 3: An interactive parametric design-through-analysis platform is proposed to help design engineers and analysts make more effective use of Isogeometric Analysis (IGA) to improve their product design and performance. We develop several Rhinoceros (Rhino) plug-ins to take input design parameters through a user-friendly interface, generate appropriate surface and/or volumetric models, perform mechanical analysis, and visualize the solution fields, all within the same Computer-Aided Design (CAD) program. As part of this effort we implement graphical generative algorithms for IGA model creation and visualization based on Grasshopper, a visual programming interface to Rhino. We are able to use the methods developed to parameterize and model a whole family of gas-turbine designs of interest to the ARL. In addition, ARL is proposing a so-called "Articulating Blade Concept", wherein, by means of rotor and stator blade pitching during operation, the operational range of the gas turbine is extended. Our paramedic design tool is used in this context, and enables ARL researchers to explore the design space more efficiently.

Training Opportunities: One PhD student at ISU was supported using the project funding. The student participated in the monthly teleconferences with the ARL project partners and reported on the progress. The student also attended scientific meetings and co-authored publications. The student received his PhD in Spring 2018, and he is now employed as an R&D engineer with ANSYS Inc.

One UG student was attracted to the project and trained to carry out basic code development and to utilize the software developed in this project. The student interned at ARL in the Summer of 2018, and continues working with the PIs and ARL researchers on gas-turbine simulations of interest to the ARL group.

The PI offered a Short Course on Computational Fluid-Strcuture Interaction as part of the EMI 2017 Conference. Research results obtained in this project were included in the Short Course material.

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as of 04-Feb-2019

Results Dissemination: The following peer-reviewed journal papers were published (** - indicates paper written jointly with ARL Researchers):

J. Yan, X. Deng, A. Korobenko, and Y. Bazilevs, “Free-surface flow modeling and simulation of horizontal-axis tidal-stream turbines”, Computers and Fluids (2016). DOI:10.1016/j.compfluid.2016.06.016.

C. Wang, M.C.H. Wu, F. Xu, M.-C. Hsu, and Y. Bazilevs, “Modeling of a hydraulic arresting gear using fluid–structure interaction and isogeometric analysis,” Computers and Fluids 142 (2017) 3-14.

Xu F, Schillinger D, Kamensky D, Varduhn V, Wang C, Hsu M-C (2016) The tetrahedral finite cell method for fluids: Immersogeometric analysis of turbulent flow around complex geometries. Computers & Fluids, 141:135–154.

** Hsu M-C, Wang C, Herrema AJ, Schillinger D, Ghoshal A, Bazilevs Y (2015) An interactive geometry modeling and parametric design platform for isogeometric analysis. Computers & Mathematics with Applications, 70:1481-1500.

Hsu M-C, Kamensky D, Xu F, Kiendl J, Wang C, Wu MCH, Mineroff J, Reali A, Bazilevs Y, Sacks MS (2015) Dynamic and fluid–structure interaction simulations of bioprosthetic heart valves using parametric design with T-splines and Fung-type material models. Computational Mechanics, 55:1211-1225.

R. Golshan, A. Tejada-Martinez, M. Juha, and Y. Bazilevs, “LES and RANS simulation of wind- and wave- forced oceanic turbulent boundary layers using the residual-based variational multiscale method with near- wall modeling”, Computers and Fluids 142 (2017) 96-108.

Y. Bazilevs, K. Kamran, G. Moutsanidis, D.J. Benson, and E. Onate, “A new formulation for air-blast fluid–structure interaction using an immersed approach. Part I: Basic methodology and FEM-based simulations”, Computational Mechanics 60 (2017) 83–100.

Y. Bazilevs, G. Moutsanidis, J. Bueno, K. Kamran, D. Kamensky, M.C. Hillman, H. Gomez, J.S. Chen, “A new formulation for air-blast fluid–structure interaction using an immersed approach. Part II: Coupling of IGA and meshfree discretizations”, Computational Mechanics 60 (2017) 101–116.

** M. Murugan, A. Ghoshal, F. Xu, M.-C. Hsu, Y. Bazilevs, L. Bravo, and K. Kerner, “Analytical study of articulating turbine rotor blade concept for improved off-design performance of gas turbine engines”, Journal of Engineering for Gas Turbines and Power 139 (2017) 102601.

** F. Xu, G. Moutsanidis, D. Kamensky, M.-C. Hsu, M. Murugan, A. Ghoshal, and Y. Bazilevs, “Compressible flows on moving domains: Stabilized methods, weakly enforced essential boundary conditions, sliding interfaces, and application to gas-turbine modeling”, Computers and Fluids (2017). doi:10.1016/j.compfluid.2017.02.006.

T. M. van Opstal, J. Yan, C. Coley, J. A. Evans, T. Kvamsdal, and Y. Bazilevs, “Isogeometric divergence-conforming variational multiscale formulation of incompressible turbulent flows”, Computer Methods in Applied Mechanics and Engineering, 316 (2017) 859-879.

Herrema AJ, Wiese NM, Darling CN, Ganapathysubramanian B, Krishnamurthy A, Hsu M-C* (2017) A framework for parametric design optimization using isogeometric analysis. Computer Methods in Applied Mechanics and Engineering, 316:944–965.

M. C. H. Wu, D. Kamensky, C. Wang, A. J. Herrema, F. Xu, M. S. Pigazzini, A. Verma, A. L. Marsden, Y. Bazilevs, and M.-C. Hsu, “Optimizing fluid-structure interaction systems with immersogeometric analysis and surrogate modeling: application to a hydraulic arresting gear”, Computer Methods in Applied Mechanics and Engineering, 316 (2017) 668–693.

Wang C, Xu F, Hsu M-C, Krishnamurthy A* (2017) Rapid B-rep model preprocessing for immersogeometric analysis using analytic surfaces. Computer Aided Geometric Design, 52–53:190–204.

A. Korobenko, Y. Bazilevs. K. Takizawa, and T.E. Tezduyar, “Computer modeling of wind turbines: 1. ALE-VMS and ST-VMS aerodynamic and FSI analysis”, Archives of Computational Methods in Engineering (2018). Accepted

for publication.

D. Kamensky, G. Moutsanidis, and Y. Bazilevs, “Hyperbolic phase field modeling of brittle fracture: part I - theory and simulations”, Journal of the Mechanics and Physics of Solids 121 (2018) 81-98.

G. Moutsanidis, D. Kamensky, J. S. Chen, and Y. Bazilevs, “Hyperbolic phase field modeling of brittle fracture: part II - immersed IGA-RKPM coupling for air-blast-structure interaction”, Journal of the Mechanics and Physics of Solids 121 (2018) 114-132.

F. Xu, Y. Bazilevs, and M.-C. Hsu, “Immersogeometric analysis of compressible flows with application to aerodynamic simulation of rotorcraft”, Mathematical Models and Methods in Applied Science, (2019). Accepted for publication.

D. Kamensky and Y. Bazilevs, “tIGAr: Automating isogeometric analysis with FEniCS”, Computer Methods in Applied Mechanics and Engineering, 344 (2019) 477-498.

Books/Book Chapters, Conference Papers, etc. (** - indicates item written jointly with ARL Researchers):

EDITED BOOK: Y. Bazilevs and K. Takizawa, “Advances in Computational Fluid-Structure Interaction and Flow Simulation: New Methods and Challenging Applications”, volume in Modeling and Simulation in Science, Engineering and Technology series, Birkhauser, 2016.

Hsu M-C, Wang C, Wu MCH, Xu F, Bazilevs Y (2016) Fluid–structure interaction modeling and isogeometric analysis of a hydraulic arresting gear at full scale. In: Takizawa K and Bazilevs Y (Eds.) Advances in Computational Fluid–Structure Interaction and Flow Simulation, Springer International Publishing.

Xu F, Kamensky D, Varduhn V, Wang C, Wasion SA, Sotomayor-Rinaldi B, Darling CN, Schillinger D, Hsu M- C (2016) An immersogeometric method for the simulation of turbulent flow around complex geometries. In: Takizawa K and Bazilevs Y (Eds.) Advances in Computational Fluid–Structure Interaction and Flow Simulation, Springer International Publishing.

** M. Murugan, A. Ghoshal, F. Xu, M.-C. Hsu, Y. Bazilevs, and K. Kerner, “Articulating turbine rotor blade concept for improved off-design performance of gas turbine engines”, In proceedings of ASME SMASIS2016, Stowe, VT, USA.

** Muthuvel Murugan, Anindya Ghoshal, Luis Bravo, Fei Xu, Ming-Chen Hsu, and Yuri Bazilevs. "Articulating Axial-Flow Turbomachinery Rotor Blade for Enabling Variable Speed Gas Turbine Engine", 2018 Joint Propulsion Conference, AIAA Propulsion and Energy Forum, (AIAA 2018-4522)

** Manoj R. Rajanna, Fei Xu, Ming-Chen Hsu, Yuri Bazilevs, Muthuvel Murugan, Anindya Ghoshal, and Luis G. Bravo. "Optimizing Gas-Turbine Operation using Finite-Element CFD Modeling", 2018 Joint Propulsion Conference, AIAA Propulsion and Energy Forum, (AIAA 2018-4657)

Honors and Awards: Yuri Bazilevs

- 2014 Highly Cited Researcher (HCR) in Computer Science

- 2015 Highly Cited Researcher (HCR) in Computer Science
- 2015 Highly Cited Researcher (HCR) in Engineering
- 2015 USACM Fellow

- 2016 Highly Cited Researcher (HCR) in Computer Science
- 2016 Highly Cited Researcher (HCR) in Engineering

- 2017 Highly Cited Researcher (HCR) in Computer Science
- 2017 Highly Cited Researcher (HCR) in Engineering

- 2018 ASCE Walter E. Huber Research Prize
- 2018 Springer book titled “Frontiers in Computational Fluid-Structure Interaction and Flow Simulation: Research from Lead Investigators under Forty – 2018” dedicated to Y. Bazilevs and K. Takizawa in celebration of their 40th birthday.
- 2018 - Appointed as E. Paul Sorensen Professor of Engineering at Brown University

Ming-Chen Hsu

- 2015 Warren Lecture at the University of Minnesota
- 2016 Highly Cited Researcher (HCR) in Computer Science

- 2017 Highly Cited Researcher (HCR) in Computer Science
- 2017 Highly Cited Researcher (HCR) in Engineering

Nikita Kozak (UG Student)

- 2018 Winner of the ARL Summer Intern Research Competition

Protocol Activity Status:

Technology Transfer: We collaborate and jointly publish with the ARL researchers. As part of this project we simulated a gas turbine design provided by ARL and reported to them the rotor-torque and turbine efficiency data for a variety of operating conditions. This knowledge transfer is used by ARL to design better gas-turbine components.

An UG student from ISU, Mr. Nikita Kozak, joined ARL as a Summer intern. He is working with the ARL partners, and is modifying and running our geometry and compressible-flow software on ARL's supercomputers to continue developing optimized gas-turbine designs.

PARTICIPANTS:

Participant Type: PD/PI
Participant: Yuri Bazilevs
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Co PD/PI
Participant: Ming-Chen Hsu

Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Fei Xu
Person Months Worked: 9.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Undergraduate Student
Participant: Nikita Kozak
Person Months Worked: 5.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Nothing to report in the upload. Please see other sections for all requested information.